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“Origins of Planetary Systems: Observations and Analysis”

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Abstract

This cooperative agreement was established with the scientific goal of understanding the conditions of early solar-type planetary systems. We investigated two facets of young solar systems: The effects on planetary bodies of young solar-type stellar mass loss, and photo-production of various organic materials due to radiation under comet-like conditions.

Stellar Mass Loss and the Young Solar System

Background

An understanding of the astrophysical and planetary conditions under which biological organisms originated on Earth is essential to an understanding and estimate of the prevalence of such organisms around other stars. Modeling of the early solar system ecoshell (region where liquid water can exist—roughly in between Venus and Mars in our solar system) however, has run into problems. The standard solar model indicates that when the solar system was born the Sun was only 70% as bright as it is today. If one examines early Mars (the outer edge of the ecoshell) there is widespread evidence for significant amounts of liquid water having existed on the surface (Carr 1987, McKay and Stoker 1989). The ancient (4.6 Gyr ago) thick CO_2 “greenhouse” atmosphere (and other gases) that have been invoked to explain the presence of liquid water on Mars (Pollack et al. 1987) have, however, become questionable since recent models including condensation (Kasting 1991) have shown that the CO_2 would have condensed out of the atmosphere at any solar luminosity less than about 84%, a brightness the Sun did not reach until long after widespread liquid water disappeared from the Martian surface. In addition, it has recently been shown that, for a few bar atmosphere under the conditions of the standard solar model, the Earth should have glaciated over (Caldeira and Kasting 1992) and would not have been able to recover once frozen.

Consequently, Doyle et al. (1993) and Whitmire et al. (1993) have suggested that the early Sun actually had 3–14% more mass than the present Sun. These mass-loss limits are constrained by both planetary as well as astrophysical conditions (the luminosity of a solar-type star scales with the mass as $L \propto M^{3.75}$, making the luminosity very sensitive to changes in mass; Iben 1967). Planetary lower limits on early solar mass-loss require liquid water to have existed on early Mars and the avoidance of complete glaciation on Earth while allowing a runaway greenhouse to have taken place on Venus. Upper limits require the avoidance of a runaway greenhouse on Earth. The Sun is also known to be depleted in lithium by a factor of about 100 which can be accounted for by mass loss of about 10% in the first Gyr after the Sun’s formation (Boothroyd et al. 1991), or a mass-loss rate about $10^{-10} M_{\odot}$ /year (solar masses per year, about 10,000 times the present solar wind rate). Magnetic braking to the present solar spin rate (Bohigas et al. 1986) would also be

expected to produce a mass-loss rate of about $10^{-10} M_{\odot}/\text{yr}$ for the first Gyr of the solar system. Solar-type stars in the Hyades star cluster (age about 0.5 Gyrs) indicate the same degree of lithium depletion while solar-type stars in the Pleiades star cluster (age about 0.05 Gyrs) do not (Soderblom et al. 1990), indicating that the lithium depletion mechanism takes place after complete star formation but within the first Gyr or so for solar-type stars. Other preliminary evidence points to an early, more massive Sun, as well. Meteorites and lunar samples indicate a significantly more flare active (Caffee et al. 1987) young Sun with some models indicating a solar wind proton flux over four orders of magnitude greater than that of today (Caffee et al. 1991). Thus, there are numerous indications that the solar system ecoshell may have been significantly effected by early mass loss from the Sun. But does this process really take place in young solar-type stars? This is what we wish to measure directly.

We selected four young, nearby solar-type stars to observe with the VLA for stellar mass loss (we obtained 29 hours and took observations at 3.6, 6.0, and 20 cm). Their young ages were determined using several techniques such as membership in a young cluster of stars, high starspot activity, and/or rapid rotation periods (for example, Soderblom et al. 1991, Gray 1992). All ages are taken to be less than 0.5 Gyrs. The expected flux, S_{ν} (in milliJanskys), from these stars can be calculated using (after Wright and Barlow 1975, Leitherer and Robert 1991, and Mullen et al. 1992):

$$S_{\nu} = 2.32 \times 10^{10} \left(\dot{M}_{\star} Z \right)^{4/3} (g_{\nu} \nu)^{2/3} (\nu_{\infty} \mu)^{-4/3} d^{-2}$$

where $\dot{M}_{\star}$ is the stellar mass-loss rate (in solar masses per year), Z is the rms ionic charge of the wind particles, γ is the number of electrons per ion, g_{ν} is the free-free Gaunt factor, ν is the frequency (in Hertz), ν_{∞} is the stellar wind velocity (in km/sec; we use a solar wind distribution), μ is the mean molecular weight of wind particles, and, finally, d is the distance to the star (in parsecs). For a typical solar-type stellar wind $Z = \gamma = \mu = 1$ may be approximated. An upper limit on distance for detectability within reasonable observing times for our stars will also be about 15 parsecs. The free-free Gaunt factor, $g_{\nu} = 10.6 + 1.90 \log T - 1.26 \log \nu - 1.26 \log Z$ at radio frequencies (Allen 1973; where T is the stellar wind temperature in degrees K). From these considerations we determined that the measurement could be made, that is, an excess stellar wind could be detected and identified by its unique 2/3 spectral index (flux depends on the frequency to the 2/3 power).

Results

An upper limit on the mass loss rate of young solar-type stars, will have substantial impact on our understanding of the early evolution of the solar system. We have reached down to the level of 7% mass loss rate with the star HD72509, but more observations are needed to reduce the error bars. We have also reached this approximate level with the star

HD39587, but have since discovered that its flare activity from a very close M-star companion will also require further observations to determine if mass loss is taking place (flare will not generally have a 2/3 spectral index). The stars HD115383 and HD206860 have also been observed but not sufficiently to have detected radio emissions indicative of mass loss at the 7% rate at present. A more detailed report of the result of these preliminary observations to detect young solar-type stellar mass loss can be found in Doyle et al. (1995). Subsequent support for this effort has not, however, been forthcoming. Nevertheless, either positive or negative results of these observations have significant impact on our understanding of the conditions under which biology originated on the early Earth as well as applicability to the evolution of young habitable zones in general.

For example, the importance of non-detection of mass loss from young solar-type stars would imply that the Sun did not lose substantial mass in the first billion years after the origin of the solar system. Completely new theories would have to be developed to explain the presence of liquid water on early Mars and the avoidance of permanent glaciation on the Earth (along with modifications of solar evolution, interpretations of meteoritic data and the cratering records, etc.). A detection of small but significant stellar wind from young solar-type stars would strongly imply that this process took place in our young solar system and takes place, in general, for very young solar-mass stars. It would provide a straightforward explanation for the presence of liquid water on early Mars and modify the timescale by which the runaway greenhouse effect took place on early Venus. Meteoritic data from this epoch could be interpreted in terms of an increased early solar wind and a mechanism could be suggested for the cause of the late heavy bombardment in the cratering record. Finally, it could provide a mechanism by which the young Earth avoided glaciation. Although it represents a small measurement on the stellar scale, such a study would have major repercussions for our understanding on the planetary scale, including the environment in which biological organisms first originated.

Organics In Comets

This part of the project was a study of the organic photochemistry of comets and interstellar ice grains. We developed an improved technique for the generation of organic residues of the type believed to reside on the surface of comets and interstellar ice grains, and modified a Gas Chromatograph-Mass Spectrometer (GC-MS) to allow for analysis of volatiles. The Infrared Spectra of the residues are an order of magnitude better than those seen before and, combined with GC-MS data, have allowed us to identify Hexamethylene-tetramine (HMT) as the major component of the organic residue, in addition to CO, formaldehyde and ethanol, which are lost as volatiles during annealing. We then studied the spectroscopy and UV photolysis of HMT in Ar and H_2O at 12 K and found that UV photolysis of HMT in the lab caused the formation of a cyano (CN) species, with the same IR signature that has been seen in the direction of the object W33A.

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